Co-deposition of B and P for Ultraprecise Bipolar devices

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The ability to fabricate 2D atomic-scale devices such as the 'single-atom transistor' [1] and, more recently dopant patch array devices [2] via the placement of donor dopants such as P and As in single planes of Si(001) has taken a large step forward, as the possibility of similarly placing acceptor dopants such as B and Al has been demonstrated. While the direct equivalents of phosphine and arsine are not stable for Gr. III elements, diborane has been used to create a p-n junction[3], and for applications where few or single dopants may be required, halide precursors, BCl_3 and $AlCl_3$ are proving promising[4,5].

In this work, we demonstrate the ability to form bipolar atomic-scale devices using BCl_3 to place boron and PH_3 to place P. The process requires a first patterning step for the boron, following by BCl_3 dosing and incorporation, and then repassivation of the surface for the second patterning step, followed by PH_3 dosing incorporation and finally burial of the device in epitaxial silicon.

A patterned Si sample with defined device areas allows for the rapid relocation of the device. In order to provide the ability to image the first incorporated dopants so that the second dopant can be aligned to the first, we have developed a high-precision dI/dV imaging method [5].

An example of a npn junction device after incorporation of both B and P dopants, but before burial of the complete device, is shown in Fig. 1. Here, the B electrode was written first, then the P electrodes were aligned to the B. Note that the dI/dV imaging method is not only providing contrast between the doped regions and the background, but also provides contrast between the p-type and n-type dopants.

(1) Fuechsle, M. *et al.* A Single-Atom Transistor. *Nat Nano* **2012**, *7*, 242–246.
(2) Wang, X. *et al.* Atomic-Scale Control of Tunneling in Donor-Based Devices. *Commun. Phys.* **2020**, *3*, 82.
(3) Škereň, T. *et al.* Bipolar Device Fabrication Using a Scanning Tunnelling Microscope. *Nat. Electron.* **2020**, *3*, 524–530.
(4) Dwyer, K. J. *et al.* Area-selective deposition and B delta-doping of Si(100) with BCl_3; Radue, M. S. *et al.* $AlCl_3$-Dosed Si(100)-2x1: Adsorbates, Chlorinated Al Chains, and Incorporated Al. arxiv **(2021)**
(5) Alemansour, H. *et al.* High Signal-to-Noise Ratio Differential Conductance Spectroscopy. *J. Vac. Sci. Technol. B* **2021**, *39*, 010601.

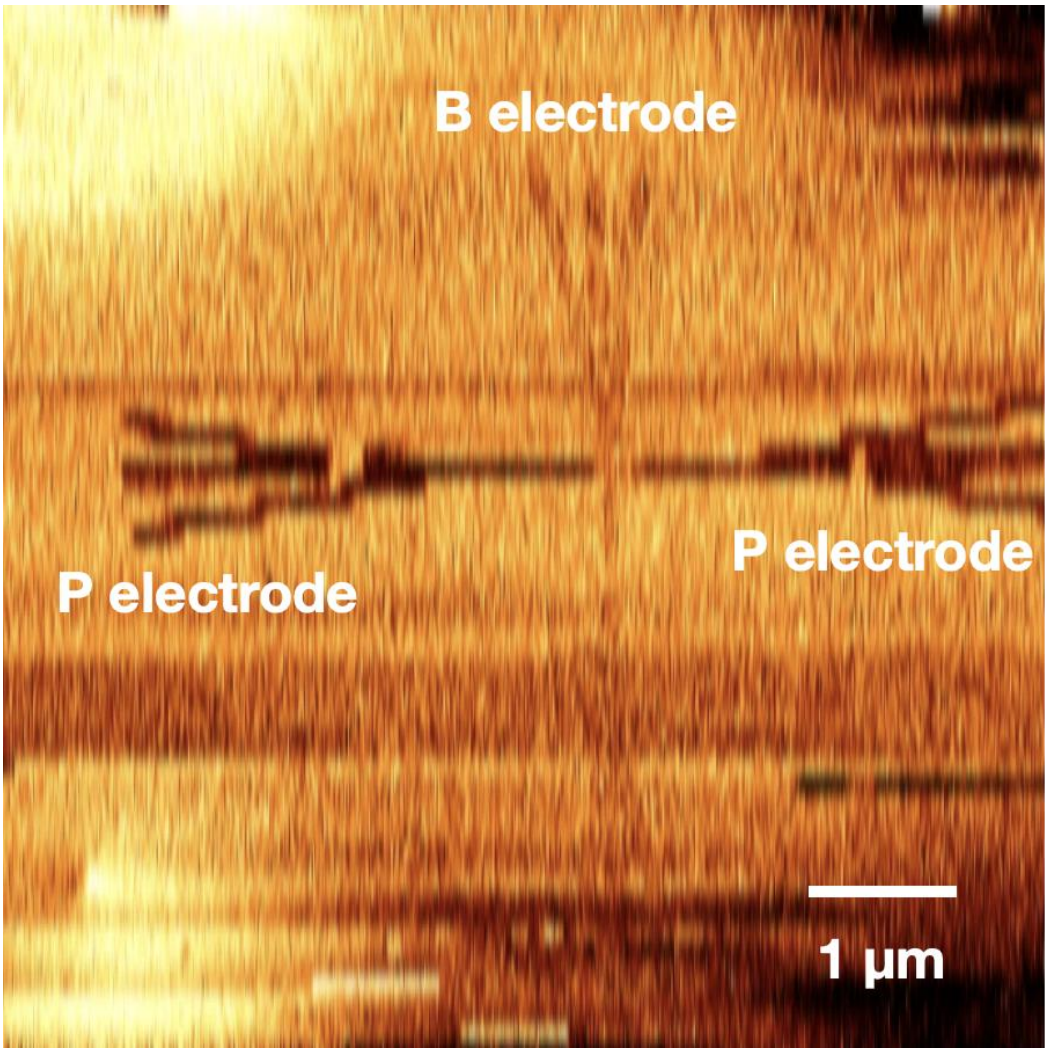

Fig. 1: dI/dV STM image of B and P electrodes forming an npn junction. The dI/dV STM image is collected in conjunction with a normal topographic image by applying a high-frequency dither to the STM bias, using the same probe as for the patterning.